Accuracy of Tissue Elasticity Measurement using Shear Wave Ultrasound Elastography: A Comparative Phantom Study

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Abstract— **Shear wave elastography (SWE) is an imaging technique using ultrafast ultrasound (20k fps) to measure tissue elasticity. This study aimed to verify the accuracy of SWE measurement compared to the gold standard and investigate the effects of size, depth, stiffness and overlapping of lesions on SWE measurements. A tissue-mimicking phantom with acoustic and shear elasticity properties similar to human breast was developed. The masses' elasticity was measured using a commercial SWE scanner and an electromechanical microtester (gold standard). Statistically significant difference ($p<0.05$) was found between the elasticity values measured using SWE and the gold standard, whereby the SWE overestimated the elasticity by a mean of 22.79±15.00 kPa. This overestimation might be due to the artefacts caused by wave interferences between the elasticity boundaries. Size and depth of lesions did not affect SWE measurement, however the depth of shear wave detection was limited to 8 cm from the surface.**

Keywords— **Shear wave elastography (SWE), ultrasound, tissue elasticity, gold standard, phantom**

I. Introduction

Elastography plays a significant role in clinical diagnosis by providing useful structural and pathological information of soft tissue, employing the strong correlation between tissue elasticity and pathological state [1].

Shear wave elastography (SWE) is a new approach to imaging and characterising tissue structures using real-time, non-invasive and reproducible methods to map tissue stiffness. Tissue elasticity is estimated quantitatively from the velocity of shear wave remotely induced in the target tissue by the acoustic radiation force of a focused ultrasonic beam [2]. SWE is advantageous over other elastography techniques for being able to highly localise the induced strain in the tissue due to complete attenuation of the shear wave within a very limited area of the focal point of a focused ultrasound beam [3]. Recent breakthroughs of SWE was achieved through the development of ultrafast imaging technique (Supersonic Imagine, Aix-en-Provence, France), in which the velocity of the shear wave induced in the tissue can be measured from the ultrasound images acquired with very high frame rate (up to 20k frames per second). Tissue elasticity is calculated using the Young's modulus formula as following:

$$E = 3\rho c^2 \quad (1)$$

where E is tissue elasticity (kPa), ρ is the local tissue density (constant and equal to 1000 kgm^{-3} in soft tissue), and c is the shear wave propagation velocity (ms^{-1}).

Since shear wave is induced in the tissue and no external vibrator is required to generate it, SWE is totally dependent on the measurement of the shear wave propagation speed in soft tissue [4]. The small changes in velocity as shear wave passes through tissue of different stiffness is detected and measured with ultrafast imaging system. With imaging in real time, the local shear wave velocity is recovered, allowing the 2-dimensional mapping of local tissue stiffness to be performed using conventional linear array probe.

As SWE is potentially developed as an important imaging modality in diagnostic imaging, the accuracy of the system in tissue elasticity estimation was assessed in this study and compared to the measurements using a high precision electromechanical microtester (current gold standard for soft tissue elasticity measurement).

II. Materials and Methods

A. Phantom Design

A soft tissue-mimicking phantom containing multiple spherical inclusions of varying diameters, elasticity and depth from the surface was designed to investigate the possible factors affecting elasticity measurement of the SWE

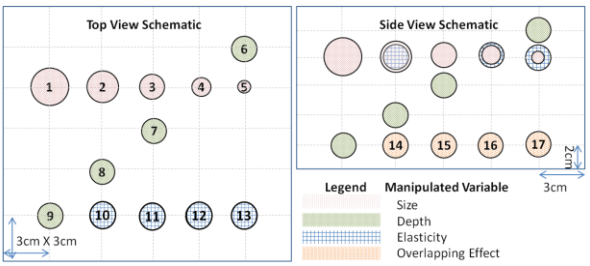

Fig. 1 Top and side view of SWE phantom schematic

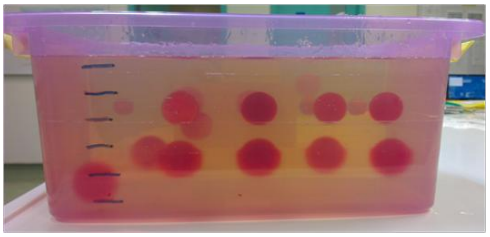

Fig. 2 Side view of constructed phantom

system. Figure 1 shows the schematic diagrams of the phantom. The water-based gel phantom, having the same acoustic velocity and elasticity as typical breast tissue, was made of animal hide gelatine powder. The stiffness of the individual inclusion varied according to gelatine content.

a) Construction of Phantom Background

A homogenous and transparent phantom background was prepared by mixing 80 g of gelatine powder extracted from lime bovine bone with 800 ml of boiling water and continuously stirred at 400 rpm for 30 min. The molten gelatine was then transferred into a plastic container to form a 20 mm-thick support layer at the bottom of the container and was left to congeal at room temperature for 8 hours. Once the support layer congealed, the spherical inclusions were placed on the support layer according to the schematic diagram. A second layer of molten gelatine was subsequently poured over the inclusions, covering both the bottom layer and the inclusions. This process was repeated until all the inclusions were successfully embedded in the phantom background (Figure 2).

b) Construction of Spherical Inclusions (Lesions)

The gelatine mixture used to construct the spherical inclusions was made by mixing gelatine with 0.5 g of calcium carbonate ($CaCO_3$), which acts as a scatterer, and 150 ml of de-ionized water. The elasticity of the inclusions was manipulated by varying the amount of gelatine added to the mixture. Additionally, a few drops of food colouring (5% Carmoisine) was added to the mixture for contrast against the transparent background to increase visibility of the inclusion.

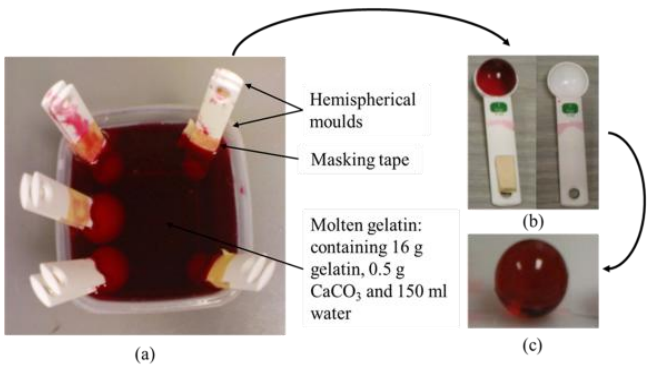

Fig. 3 Spherical inclusion moulding procedure

The moulding procedure of the spherical inclusion (Figure 3) involved immersing a pair of hemispherical moulds in the molten gelatine mixture and securing the moulds together with masking tape once each hemispherical mould were wholly filled. After the gelatine was completely set, the moulds were carefully detached to produce the spherical inclusions. Spherical inclusions of different sizes were made using pairs of hemispherical moulds with varying diameters. Using the same batch of gelatine mix, each inclusion was made in pair; one was used for *in vivo* SWE measurement, while the other for *in vitro* elasticity measurement (gold standard).

B. Phantom Elasticity Measurement using SWE System

Elasticity of the inclusions was obtained using a SWE ultrasound system with a linear probe within a frequency range of 7.5 to 15 MHz. The axial and lateral resolutions at -6 dB ranged from 0.3 to 0.5 mm and 0.3 to 0.6 mm, respectively. The probe was gently placed (without hard pressing) on the surface with generous amount of acoustic gel applied to avoid air gap between the interfaces.

The B-mode image was acquired prior to SWE acquisition. Obtaining a B-mode (brightness) image of high quality was imperative to ensure the effective transmission of the focused beams, which in turn generates the acoustic force and shear wave, as well as that of the plane wave pulses, which capture the shear wave. After B-mode acquisition, the SWE application was activated and a colour map representing the elasticity values was superimposed on the B-mode image.

The region of interest (ROI) was defined over the inclusion area, allowing the system to quantify elasticity values within the ROI. The average of the mean elasticity values obtained was calculated for each inclusion.

C. In vitro Measurement of Soft Tissue Elasticity (Gold Standard)

The duplicate set of the inclusions was sent for *in vitro* elasticity measurement using a calibrated electromechanical microtester system (model 5848, Instron Co, USA). This is a destructive method using mechanical compression on the samples, resulting in the destruction of the samples at the end of the test. The spherical inclusion was first cut into cylindrical shape with 2:3 ratio (diameter:height) as required by the system to allow uniform stress to be applied on the surface of the samples and to reduce the possibility

of stress non-uniformities at the sample edges. The compressive test was done at a displacement-control rate of 0.1 $mm.min^{-1}$ until the elastic limit of the sample was reached. A graph of compressive stress (kPa) against strain was obtained from the software and the Young's modulus of each sample was estimated from the initial slope of the stress-strain curve in the linear elastic region.

The elasticity of each inclusion measured by the SWE and the Instron microtester were compared statistically using the paired-sample t-test with 95% confidence interval.

D. Factors Affecting Elasticity Measurement in SWE

The elasticity of every inclusion within the phantom, which varied in depth, diameter, stiffness and overlapping structures were obtained using the SWE system to investigate factors affecting the measurement accuracy.

III. Results

A. Comparison of Elasticity Measured using SWE and the Gold Standard

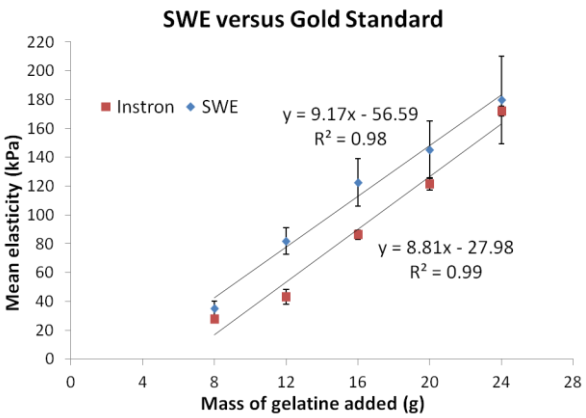

Fig. 4 Comparison of elasticity values measured by SWE and Instron.

Figure 4 shows a significant difference ($p < 0.05$) between the elasticity values measured by the two different systems, at which the elasticity measured by the SWE system was overall higher than the gold standard (Instron microtester) by a mean of 22.79 ± 15.00 kPa.

B. Factors Affecting Elasticity Measurement in SWE

Figure 5 shows a strong linear relationship ($R^2 = 0.985$) between the mean elasticity (kPa) and the mass of gelatine added to the spherical inclusion (i.e. stiffness). No relationship was observed between the size (Figure 6) and depth of the inclusion with the measured elasticity. There was a limitation in SWE measurement whereby the useful depth for shear wave detection was restricted to a maximum of 5 cm using the linear probe and 8 cm using the curvilinear probe. Therefore the elasticity for the inclusions seeded more than 8 cm from the surface could not be measured.

IV. Discussion

A phantom that mimics both acoustic and elastic properties of soft tissue was constructed in this study. Although there are various tissue mimicking materials (TMMs) available for elastography phantoms, water-based gelatine was chosen because it has a wide range of elasticity approximating that of soft tissues (5 – 135 kPa) [5]. Furthermore, the phantom elasticity, sound speed, absorption and scattering coefficients can be independently controlled by changing the gelatine to water ratio, amount of gelatine and amount of scatterer added, respectively. The phantom elasticity increased almost linearly ($R^2 = 0.985$) with the mass of gelatine in the mixture. A trace amount (~0.5 g) of $CaCO_3$ was added to enable scattering and absorption properties of the phantom. Gelatine does not exhibit the drawbacks posed by other types of TTMs. For example, copolymer-in-oil is

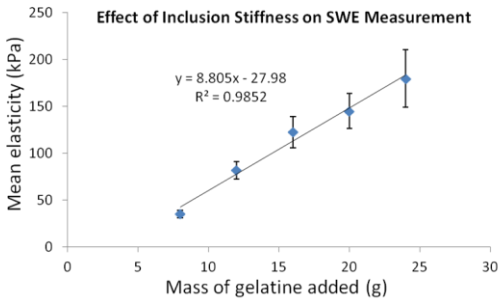

Fig. 5 Graph showing effect of inclusion stiffness on SWE measurement.

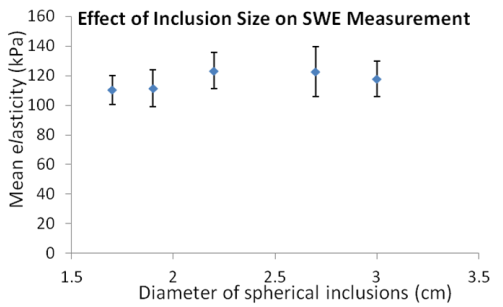

Fig. 6 Graph showing effect of inclusion size on SWE measurement.

unable to achieve the same range of acoustic velocities as soft, while polyarcylamide gel is fragile and toxic [6].

This study shows that the tissue elasticity measured by SWE was significantly higher than the gold standard. The overestimation might be attributed to two factors. Firstly, the SWE system assumes that the density, ρ of all tissues in the body equals to 1 $g.cm^{-3}$ whereby the elasticity measurements are computed based on this assumption. In reality, there is variation between ρ of different types of tissues.. The degree of dependency of the measured elasticity on the actual tissue density would be an area for future research in SWE. Secondly, the overestimation might be due to the presence of elasticity boundaries between media. It has been reported that elasticity boundaries causes shear wave reflection which introduces an artefact in elasticity measurements [7]. Shear wave reflection at the boundaries could cause either constructive or destructive interference, and consequently results in underestimation or overestimation of the actual elasticity values. These artefacts can be complex especially when multiple elastic reconstructions are combined to form a single elasticity image.

A spatio-temporal directional filter has been developed to separate the incident and reflected propagating shear waves [8] and has been shown to reduce the artefacts in the reconstructed shear modulus map of a stiff inclusion, as well as to improve the signal-to-noise ratio of the acquired data. Promising results have been demonstrated in elastic finite-difference time-domain simulation and in vitro phantom experiments, and it is therefore highly recommended to apply such a filter in transient shear wave applications to improve the accuracy of tissue elasticity measurement.

Elasticity increased linearly ($R^2 = 0.985$) with increasing mass of gelatine added to the inclusions. However, it was also observed that the standard deviations of elasticity measurement increased with increasing stiffness of the inclusions, indicating that the reproducibility of elasticity values decreased for stiffer tissues. This effect can also be explained by the differences in elasticity boundary, previously explained, which becomes larger as elasticity and density contrast between inclusion and background increases. Further study is recommended to investigate the effects of elasticity boundaries on the accuracy of SWE measurement. On the other hand, the sizes of inclusions did not affect the elasticity values measured using SWE. The effects of depth and overlapping inclusions could not be fully assessed in this study due to the system's limitation in depth detection. A separate phantom may be made to investigate the overlapping effects.

V. Conclusions

SWE ultrasound imaging combines both ultrasound images and quantitative tissue elasticity information for a better diagnosis outcome. Many researches have shown that SWE has great potential to improve sensitivity and specificity of breast, liver, thyroid and prostate diseases. However the accuracy of the elasticity measurement needs to be validated against a gold standard. This study shows that the tissue elasticity derived from the commercial SWE system were consistently higher than the gold standard, which is most probably due to wave interference at the elasticity boundary. In order for SWE to be incorporated into clinical diagnostic practice, it is vital to identify a solution to overcome these artefacts.

Acknowledgment

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Conflict of Interest

The authors declare that there is no conflict of interest in this study.

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